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Policy Analysis

Assessing Regional Strategies to Cope with Drought, Climate, and Environmental Flow Policy Impacts for a Sustainable Water Supply: A Case Study of the Bay Area

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ABSTRACT: California's Bay-Delta watershed encompasses 40% of the state's runoff and serves water supply and irrigation needs throughout the state. A recently amended policy attempts to rebalance water supply and ecological outcomes by requiring 40% of the flow to remain in-stream in the Tuolumne River and other tributaries between February 1 and June 30 each year. This policy impacts water supply diversions serving millions of customers in the San Francisco Bay Area. This work analyzes possible regional coping responses in the context of climate and policy uncertainty, exploring the effectiveness of various strategies to mitigate climate and policy impacts and improve future water supply outcomes. We find that climate uncertainty has a dominant impact on three measures of water supply performance: the frequency of full storage reserves, minimum storage level, and uncaptured flow remaining. Coping interventions in the ranges considered (0−500,000 acre-feet/0−620 million m^3 new storage; 0−60,000 acre-feet per year/0−70 million m^3 per year new supplies) can serve to mitigate climate impacts and to fully or partially offset the impact of the in-stream flow policy. Regardless of the policy, coping interventions are needed to avoid critically low storage levels. Our analysis indicates that recharge may be an effective strategy to increase capture of Tuolumne River streamflow, with an expected yield of 0.15−0.51 units of flow captured per unit of recharge capacity added, compared to reservoir expansion, with an expected yield of 0.05−0.07 units of flow captured annually per unit of volume capacity added.



KEYWORDS: *water supply planning, drought response, reliability, ecological flows, Bay-Delta Plan, decision support*

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INTRODUCTION

Water Supply and the Bay-Delta. California's Bay-Delta watershed encompasses 40% of the state's runoff and serves the water supply and irrigation needs of 30 million people.[1] The state seeks to manage this system according to "coequal goals" of water supply and ecosystem protection,[2] yet sharp declines in migratory fish populations over recent decades indicate that present management is not adequately supporting ecosystem health.[3] High-stakes challenges of balancing ecological, agricultural, and urban water needs are not unique to this region but are shared widely throughout the American West.

In California, water quality in the Delta is largely dependent on flow diversions and is regulated through the Water Quality Control Plan for the San Francisco Bay/Sacramento-San Joaquin Delta Estuary (Bay-Delta Plan).[4] In an effort to rebalance water supply and ecological outcomes, amendments to the Bay-Delta Plan were adopted in 2018 and require 40% of unimpaired flow (i.e., the flow generated by the watershed assuming no upstream diversions) to remain in-stream in the Tuolumne River and other tributaries between February 1 and June 30 each year.

In response to the new in-stream flow requirement, a group of water utilities, agencies, and others has proposed alternative Voluntary Agreements, which seek to reduce the required in-stream flows to a level below 40% by also incorporating nonflow measures like habitat restoration, predation control, and monitoring.[5] A report prepared by the State Water Board, the California Department of Water Resources, and the California Department of Fish and Wildlife finds that the proposed Voluntary Agreements are generally expected to improve ecological outcomes compared to pre-Amendment baseline conditions.[6] However, Marcus et al.[7] argue that the baseline for comparison should be the expected post-Amendment conditions, since the purpose is to achieve the

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Table 1. Selection of Reliability Metrics Describing Various Dimensions of Water Supply Performance

Water Supply Objective	Label	Metric	ref
Reservoir storage	Resilience	Relative storage (ratio of current reservoir storage to total reservoir capacity)	20
	Reliability	Proportion of simulations in which relative reservoir storage stays above 20%	21,22
	Vulnerability	Ratio of total storage to annual consumptive demand	23
	Risk of failure	Proportion of historical years that, if occurring over the next year from the present, would result in reservoir storage falling below a user-defined threshold	23
Meeting demand	Reliability	Ratio of water supply to demand	20
	Cumulative supply deficit	Shortfall of water supply relative to demand	24
	Resilience	Index derived from supply stress, supply diversity, water use, and demand diversity	25
	Robustness	Proportion of scenarios meeting performance threshold defined by maximum allowable magnitude and frequency of water supply shortage	26
Multicriteria/variable performance	Robustness	Maximin (maximize the worst performance)	27
		Maximax (maximize the best performance)	
		Optimism-pessimism rule (maximize a weighted combination of best and worst performance)	
		Minimax regret (minimize the maximum regret)	
		Principle of insufficient reason (maximize expected performance, treating all future states as equally likely)	
		Proportion of simulations with >99% of demand met, <20% restriction frequency, and <5% worst-case cost relative to annual revenue	23

Table 2. SFPUC Reliability Metrics and Targets from Its Long Term Vulnerability Assessment[30]

Label	Metric	SFPUC Target
Delivery reliability	Fraction of years with no rationing	≥90%
Frequency of 20% rationing	Fraction of years containing mandatory 20% rationing	≤5%
Duration of rationing	Consecutive years with rationing	≤5 years (for Design Drought planning, ≤6.5 years)
Storage reliability	Fraction of years in which storage exceeds 2.3 years of rationed supply	None (≥99%[a])
Maximum annual supply deficit	Greatest cumulative difference between demand and deliveries across a single year	None (≤59,300 AF[a]; 73 million m^3)
Maximum cumulative supply deficit	Greatest cumulative difference between demand and deliveries across a continuous rationing period	None

[a]Reference value assumed in Long-term Vulnerability Assessment.

goals of the policy and not merely to outperform the existing conditions. The policymaking process continues as the State Water Board evaluates the proposed Voluntary Agreements and as the proposal is refined in response to input from the State Water Board, the public, and other stakeholders.[8]

Reliability Goals. The State of California recognizes a basic right to reliable water supply in its Human Right to Water policy, which states that all people have the right to "safe, clean, affordable, and accessible water".[9] Good water supply performance is essential for human, environmental, and economic health,[10] yet perfect water supply performance is impossible, and approaching perfect performance comes with environmental and economic trade-offs that at some point will begin to outweigh the incremental improvements in water supply performance.[11−13] Identifying a target performance level is no small task, as communities must consider heterogeneous attitudes toward reliability and risk, as well as substantial uncertainty in future demand, climate patterns, and regulatory policies.

Water providers can use reliability goals to communicate their motives to stakeholders and to guide their decision making toward these desired outcomes. When conflicts arise, the goals provide a framework to distinguish between whether the system is failing to meet stated goals or whether the goals themselves are unsatisfactory. Although state,[14] national,[15] and international[16] standards provide detailed criteria for the acceptable quality of drinking water supplies, no such detailed, quantitative standards exist for what constitutes acceptable reliability in drought.

In California, Title 22 Drinking Water regulations outline delivery requirements related to peak hourly and daily demands but do not speak to delivery performance for annual or multiannual demands (e.g., minimum annual reliability).[17] For annual and multiannual time scales, urban water suppliers are required to conduct a Reliability Assessment comparing projected supply and demand totals under various hydrologic scenarios.[18] They are given the qualitative instruction to "make every effort to ensure the appropriate level of reliability in [their] water service",[19] but the water suppliers are left to define and pursue their own quantitative targets, which can take many forms. Researchers who study water supply reliability likewise take a variety of approaches to define and measure this dimension of water supply performance, as shown in Table 1. These reliability-oriented metrics measure performance in different ways but generally emphasize water supply objectives of maintaining adequate storage, meeting customer demand, or maximizing multiobjective performance. Beyond defining reliability metrics and target levels for these metrics, water supply actors must formulate additional layers of policy connecting measured conditions to their operational response (e.g., at what storage level should rationing be implemented?).

Regional Water System Planning. Faced with the task of defining its own reliability targets, the San Francisco Public Utilities Commission (SFPUC) in its Long-term Vulnerability Assessment defines six performance metrics, with the corresponding targets communicating reliability goals (Table 2). SFPUC's metrics focus primarily on meeting customer

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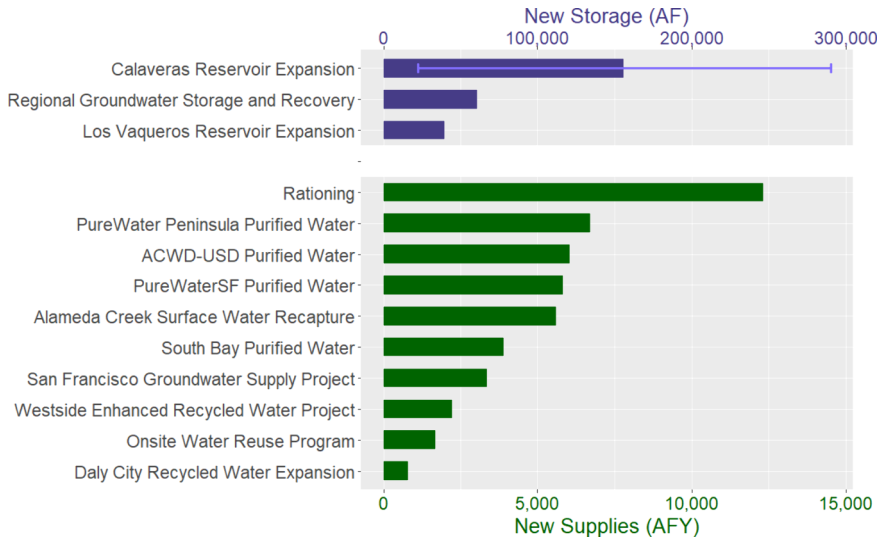


Figure 1. Local and regional water supply projects discussed in SFPUC's Alternative Water Supply Plan.[31] Detailed project descriptions can be found in the referenced plan document. Proposed projects add up to 123,000−391,000 AF in new storage capacity (blue bars) and up to 49,000 AFY in new water supplies (green bars).

demand and secondarily on maintaining adequate storage; these general objectives are consistent with Table 1, and the metrics themselves are tailored to SFPUC's system, context, and priorities. These reliability efforts are situated within a larger regional commitment to water supply reliability, as SFPUC also participates in collaborative planning efforts including the San Francisco Bay Area Integrated Regional Water Management Plan[28] and the Bay Area Regional Reliability Drought Contingency Plan.[29]

To build toward these reliability targets, SFPUC has identified a collection of local and regional water supply projects encompassing groundwater, surface water, potable and nonpotable reuse, on-demand rationing, and storage (Figure 1). With a planning horizon of 2045, SFPUC outlines projects that could contribute up to 391,000 acre-feet (AF; 482 million m^3) of new storage capacity and up to 49,000 acre-feet per year (AFY; 60 million m^3 per year) of new supplies/reduced demand.[31] In its planning, SFPUC uses a design drought lasting 8.5 years and assumes that new storage reserves would contribute a uniform annual supply starting one year into the drought (i.e., the new storage amount is distributed across 7.5 years). This assumption implies the ratio that 7.5 units of new storage capacity are worth 1 unit of new annual supply based on the water supply balance in dry years.

This paper examines the effectiveness of these and other regional water supply strategies to cope with the water supply challenges of climate, Bay-Delta policy, and drought. We analyze future water supply performance under climate and policy uncertainty, considering how the proposed projects measure up in light of the level of coping intervention that would be needed to achieve various levels of performance. We do not seek to address every possible facet of reliability nor an exhaustive set of hydrologic realizations but instead to demonstrate how a multidimensional reliability analysis can yield compact decision support insights for water supply performance influenced by climate, policy, and planning. We focus on water supply performance first to address how much and what kind of coping intervention might be needed to avoid undesirable outcomes under uncertain conditions. Essential future work can then build upon this performance-based analysis by exploring the specific project types, projects, costs, and other feasibilities involved in implementing the level of coping intervention needed to achieve the desired performance.

METHODS

Water Supply Model. This analysis models the Tuolumne River portion of the Hetch Hetchy Regional Water System in R using a monthly time step and allocating available water toward urban deliveries, water rights release, ecological release, evaporation, and change in storage. In any given month, the total water available to allocate consists of that month's Full Natural Flow (i.e., the flow generated by the Tuolumne watershed above the Don Pedro rim dam), along with the stored water available to SFPUC in Tuolumne system reservoirs. The total available water is then distributed among that month's system demands, including urban deliveries, water rights release to senior agricultural users downstream, ecological release to meet Bay-Delta Plan requirements, and evaporative losses from the reservoirs. Storage levels are then debited or credited according to whether that month's demand exceeded SFPUC's rights to the Full Natural Flow. In the simulation, demands are met in full whenever sufficient water is available, since water conservation measures are included separately in the analysis as a possible coping intervention.

We represent uncertain future hydrology using the set of climate projections utilized by California in its Fourth Climate Change Assessment[32] and by the Intergovernmental Panel on Climate Change in its Fifth Assessment Report.[33] Our model uses eight streamflow scenarios from Pierce et al.[34] that result from four global climate models, each evaluated at two emissions assumptions, selected to span a range of climate outcomes. Pierce et al. evaluate a set of 32 global climate models, narrow this set to 10 models best suited to California, and from this set identify 4 models that generally represent the range of outcomes produced by the set of 10: the HadGEM2-ES model as generally the most "warm/dry", CanESM2 as "average", CNRM-CM5 as "cool/wet", and MIROC5 as "most

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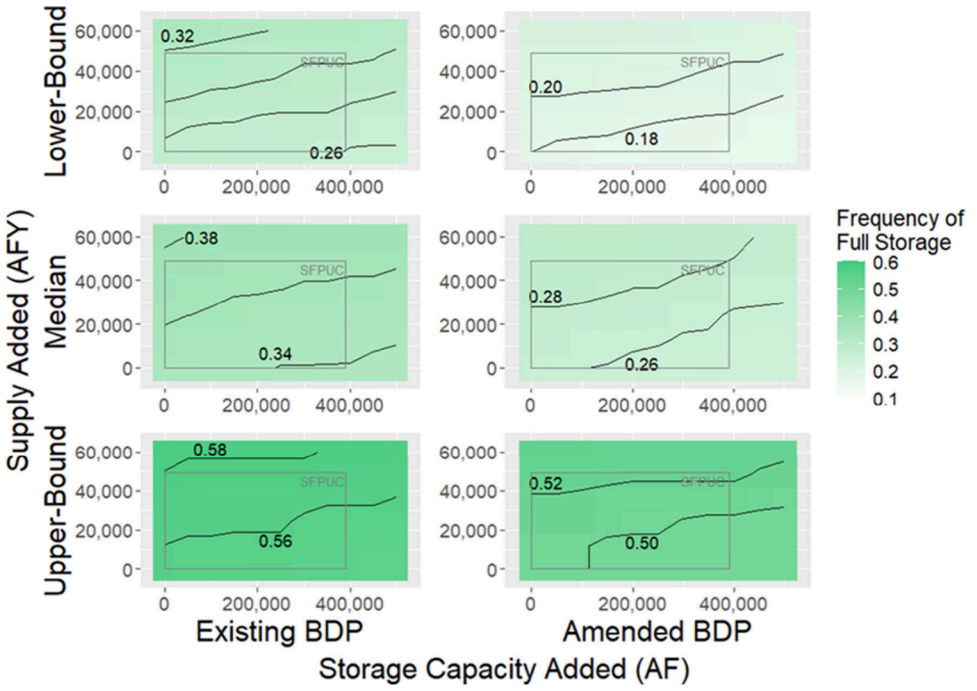


Figure 2. Frequency of full storage reserves during a 30-year simulation. The left column corresponds to the Existing BDP policy, and the right column corresponds to the Amended BDP policy. The top, middle, and bottom rows correspond to lower-bound, median, and upper-bound performance across climate scenarios. The axes of each plot show intervention actions: storage capacity added on the horizontal axis and supply added on the vertical axis. Contour lines at 0.02 spacing show equal performance across various intervention combinations, and high and low contour values are annotated on each plot. The gray box indicates the intervention range is considered in the SFPUC's Alternative Water Supply Plan.[31]

unlike the other three". Detailed descriptions of our model and the Regional Water System are available in Gile et al.[35]

Policy Scenarios. This analysis considers two policy scenarios, the Existing Bay-Delta Plan ("Existing BDP") and the Amended Bay-Delta Plan ("Amended BDP"), which act as lower and upper bounds, respectively, for the future unimpaired flow requirement on the system. The Amended BDP scenario reflects the policy amendments passed in 2018.[4] However, ongoing negotiations of Voluntary Agreements that include flow and nonflow measures[5] may result in flow-based requirements somewhere between the levels set by the existing and amended policy. Comparing water supply performance between these bounding scenarios gives a sense of the scale of influence that unimpaired flow policy has on water supply outcomes.

Coping Interventions. With the assumption that water rights entitlements and ecological flow policy are set beyond SFPUC's control, there are fundamentally two intervention options available to SFPUC for manipulating the Regional Water System water balance to improve water supply outcomes: increasing storage capacity or increasing supply relative to demand.

1. Increase storage capacity ("New Storage"): Increasing storage capacity does not itself introduce more water into the system, but it does allow SFPUC to capture more of the variable Tuolumne streamflow when it occurs so that the water can be used later as it is needed. New Storage projects could take various forms including aquifer storage and recovery, reservoir expansion, or water banking.
2. Increase supply relative to demand ("New Supplies"): Interventions in this category function to satisfy demand and fill up storage capacity, either by bringing additional water into the system (e.g., through production or import) or by reducing demand to free up water within the system. Increasing supply or decreasing demand each makes more water available to allocate in the present. Depending on the state of the system, New Supplies could have the effect of extending the life of storage reserves, of building storage reserves for the future, or of contributing excess flow released downstream.[35] New Supplies could include projects like reuse, stormwater capture, desalination, conservation, or water transfers.

Our analysis considers intervention portfolios that include New Storage and New Supplies in various combinations. We evaluate possible intervention responses encompassing 0−500,000 AF New Storage (at 50,000-AF increments; 0−620 million m^3 at 60-million-m^3 increments) in combination with 0−60,000 AFY New Supplies (at 12,000-AFY increments; 0−70 million m^3 per year at 15-million-m^3-per-year increments). These ranges extend slightly beyond the scale of the projects currently being considered by SFPUC,[31] so that the analysis can assess levels of intervention within and beyond what has been proposed. To focus on the long-term performance rather than the particular sequence of the hydrologic projections, the coping interventions are assumed to be available immediately from the beginning of the analysis window. Our analysis explores the water supply performance that could be expected with various combinations of interventions in effect, though of course many other considerations such as cost and construction are also crucial to the planning conversation.

Performance Metrics. The analysis focuses on three dimensions of water supply performance:

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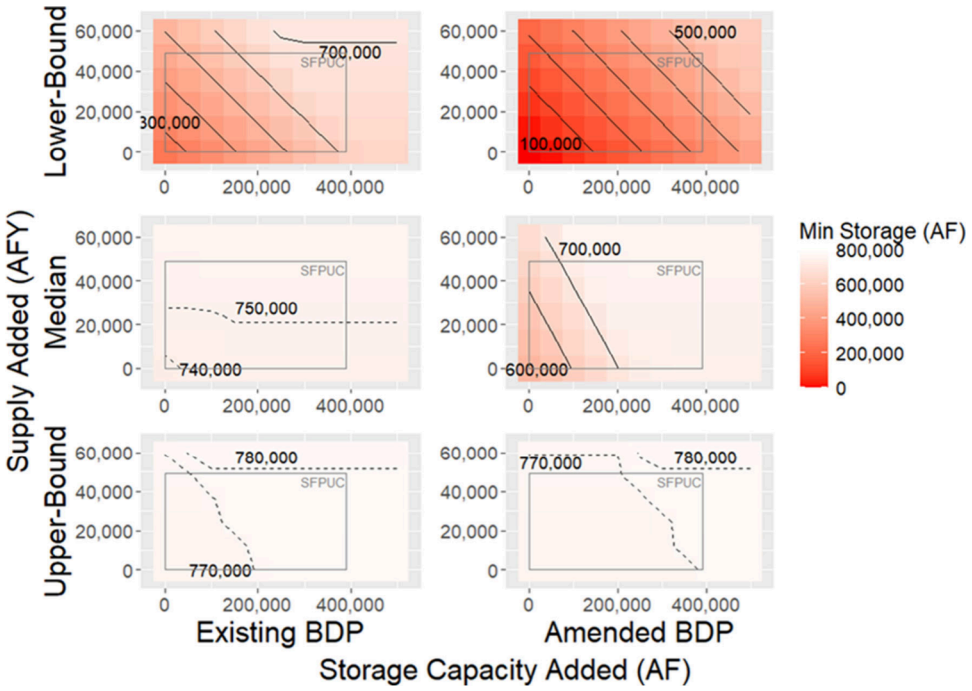


Figure 3. Minimum storage level experienced during a 30-year simulation. The left column corresponds to the Existing BDP policy, and the right column corresponds to the Amended BDP policy. The top, middle, and bottom rows correspond to lower-bound, median, and upper-bound performance across climate scenarios. The axes of each plot show intervention actions: storage capacity added on the horizontal axis and supply added on the vertical axis. Contour lines at 100,000 AF spacing (solid) and 10,000 AF spacing (dashed) show equal performance across various intervention combinations, and high and low contour values are annotated on each plot. The gray box indicates the intervention range considered in the SFPUC's Alternative Water Supply Plan.[31]

1. High-end performance − How often are storage reserves full? Calculated as the number of months in which storage level is equal to full capacity, divided by the total number of months in the analysis window.
2. Low-end performance − What is the minimum storage level experienced during the simulation? Equal to the minimum storage level that occurs during the simulation.
3. Uncaptured flow − How much uncaptured flow remains? Calculated as the cumulative total of water released from SFPUC storage due to insufficient storage capacity, rather than due to delivery obligation or losses.

Together, these metrics speak to the anticipated performance range and watershed impact of a given scenario. These metrics apply to SFPUC's urban water supply and may not reflect the outcomes experienced by other water users (e.g., agriculture) served by the Tuolumne River. Considering both high- and low-end performance is essential because the intervention scenario that performs very well at its best may also perform very poorly at its worst.[36] We measure performance by emphasizing storage rather than delivery because the amount in storage reflects the overall health of the system and its potential to supply future needs. By contrast, the amount delivered reflects the drought response, providing more limited information about the state of the system. For example, if full demand is not met due to voluntary rationing in the early stages of drought, this is very different from if full demand is not met due to reservoirs being too low to supply the full need. Storage level metrics distinguish between these cases in a way that delivery metrics do not.

The third metric, uncaptured flow remaining, reflects the opportunity for additional utilization of Tuolumne streamflow to which SFPUC has rights. This third metric might also be considered a measure of uncredited ecological release, i.e., in-stream flow that travels downstream in excess of policy requirements.

Visualizing Uncertainty. For each intervention response, the value of a given performance metric varies depending on the hydrologic scenario. This means that the performance metric associated with a particular intervention takes eight different values for the eight hydrologic scenarios considered. To represent climate uncertainty, this analysis illustrates the range of outcomes by reporting the lower-bound (minimum), upper-bound (maximum), and central (median) values of the performance metric within this set of eight. Our treatment of uncertainty incorporates elements from a broader approach known as decision making under deep uncertainty, which reverses the traditional "predict-then-act" planning process and instead focuses on how a proposed action might perform across multiple possible futures.[37,38]

RESULTS

Water Supply Performance with Coping Interventions. *Frequency of Full Storage.* Water supply performance measured by the frequency of full storage is shown in Figure 2. The frequency of full storage was simulated across dimensions of climate uncertainty (top, middle, and bottom rows), policy alternatives (left and right columns), and coping intervention (vertical and horizontal axes of each individual plot).

In a prospective analysis, full storage reserves are expected to occur with a frequency as high as 58% or as low as 16%, depending on the climate, policy, and intervention. Adding supplies tends to increase the frequency of full storage, while adding storage capacity tends to slightly decrease this

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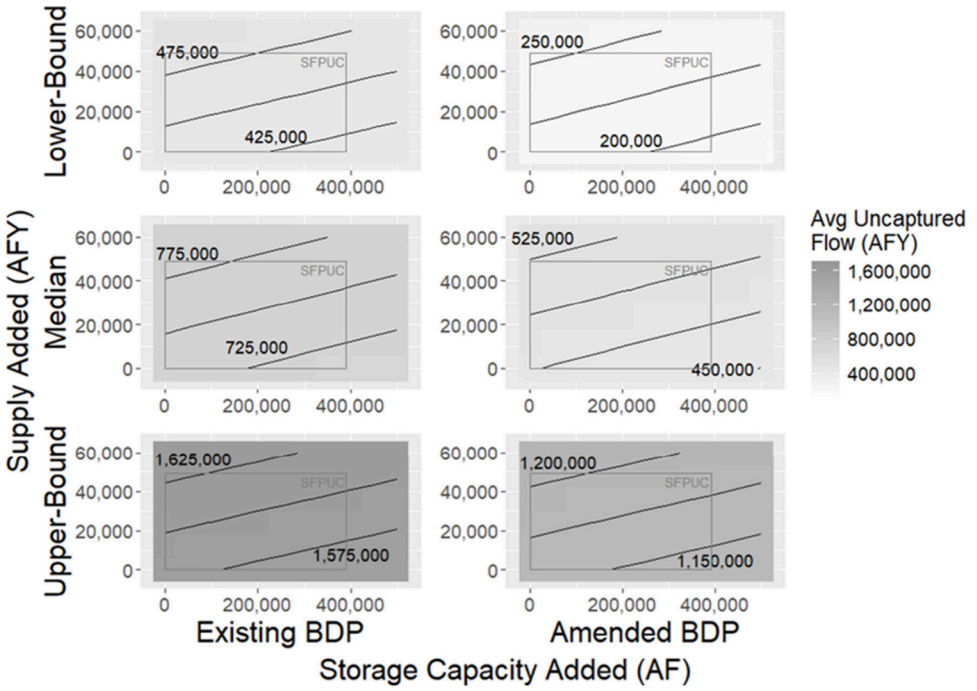


Figure 4. Average annual uncaptured flow remaining during a 30-year simulation. The left column corresponds to the Existing BDP policy, and the right column corresponds to the Amended BDP policy. The top, middle, and bottom rows correspond to lower-bound, median, and upper-bound performance across climate scenarios. The axes of each plot show intervention actions: storage capacity added on the horizontal axis and supply added on the vertical axis. Contour lines at 25,000 AF spacing show equal performance across various intervention combinations, and high and low contour values are annotated on each plot. The gray box indicates the intervention range considered in the SFPUC's Alternative Water Supply Plan.[31]

frequency because the expanded capacity requires a higher storage level to fill it. The latter trend may seem contradictory because adding storage capacity should benefit water supply performance; however, this metric captures effects that may be driven by relative rather than absolute storage levels, such as operating policy and public perception of system health. The contours connecting equal performance as measured by full storage are oriented more horizontally than vertically, indicating greater sensitivity to new supplies and/or reduced demand than to new storage capacity.

In Figure 2, on average, the left-column plots for the Existing BDP policy case display frequencies 8 percentage points greater than the right-column plots for the Amended BDP policy case, indicating that the cost of the Amended BDP policy could be 8% of the time no longer spent at full storage. The upper-bound plots display frequencies 29 percentage points greater than the lower-bound plots, indicating that climate uncertainty spans 29% of time at full storage. By comparison, typical variation within each plot panel is 5 percentage points, indicating that the intervention response could influence whether 5% of time is spent at full storage. Compound effects are also visible in the figure. For example, climate uncertainty spans 27% of time at full storage under the Existing BDP policy but 32% under the Amended BDP policy, indicating that the policy impacts sensitivity to climate change for this performance metric. The relative sizes of these influences suggest that coping interventions in the range considered can partially but not totally offset the effects of climate and policy influences on the frequency of full storage reserves.

Minimum Storage Level. Water supply performance measured by the minimum storage level experienced is shown in Figure 3. The minimum storage level experienced was simulated across dimensions of climate uncertainty (top, middle, and bottom rows), policy alternatives (left and right columns), and coping intervention (vertical and horizontal axes of each individual plot).

Depending on climate, policy, and intervention, the minimum storage level experienced is expected to be as low as zero or as high as 780,000 AF (960 million m^3; approximately equal to the initial storage condition of 790,000 AF/970 million m^3, which reflects observed conditions at the beginning of the simulation period). Adding supplies or adding storage capacity each tends to increase the minimum storage level, especially in the drier range of climate uncertainty, where minimum storage is far below the initial storage conditions. In the wetter range of climate uncertainty, the effects of intervention are less pronounced.

On average, the left-column plots display storage levels 100,000 AF (120 million m^3) greater than the right-column plots, indicating that the cost of the Amended BDP policy could be a 30-year minimum storage level 100,000 AF (120 million m^3) lower. The size of the policy impact varies considerably across the climate range, with a larger 260,000 AF (320 million m^3) impact under a drier climate, and a negligible (<10,000 AF; 10 million m^3) impact under the wettest climate considered. The upper-bound plots display levels 330,000 AF (410 million m^3) greater than the lower-bound plots, indicating the span of climate uncertainty on the 30 year minimum storage level. This climate impact varies by policy, with the Amended BDP policy resulting in larger climate uncertainty of 460,000 AF (570 million m^3) compared to 200,000 AF (250 million m^3) with the Existing BDP policy. Typical variation within each plot panel is 230,000 AF (280

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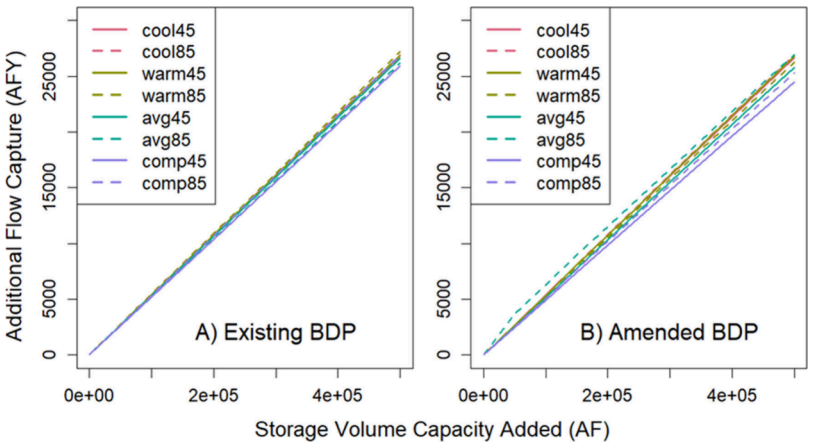


Figure 5. Additional flow captured vs storage volume capacity added under (A) Existing BDP and (B) Amended BDP policy scenarios for eight climate scenarios. Individual climate scenarios are labeled according to their classification by Pierce et al.[34] (cool, warm, average, and complementary) and their assumed emissions level (Representative Concentration Pathways of 4.5 and 8.5).

million m^3), indicating that the intervention response could influence the minimum storage level on the order of hundreds of thousands of acre-feet, with the effect greatest under a drier climate. The relative sizes of these influences suggest that while climate uncertainty has a large impact on the minimum storage level, a strategic coping intervention could fully offset the policy impact.

Uncaptured Flow Remaining. Water supply performance measured by the amount of uncaptured flow remaining is shown in Figure 4. The uncaptured flow remaining was simulated across dimensions of climate uncertainty (top, middle, and bottom rows), policy alternatives (left and right columns), and coping intervention (vertical and horizontal axes of each individual plot).

In a prospective analysis, the uncaptured flow that SFPUC does not have the capacity to store is expected to average as low as 190,000 AFY (230 million m^3 per year) or as high as 1,600,000 AFY (2000 million m^3 per year), depending on climate, policy, and intervention. Adding storage capacity tends to decrease the amount of uncaptured flow because it gives the system the ability to capture a greater volume of Tuolumne streamflow as it is available. By contrast, adding supplies tends to increase the amount of uncaptured flow with the assumption that new supply projects would be utilized first and would partially offset the Tuolumne streamflow needed to meet demand. The contours of uncaptured flow performance are oriented more horizontally than vertically, indicating greater sensitivity to new supplies and reduced demand than to new storage capacity.

On average, the left-column plots display uncaptured flow amounts 300,000 AFY (370 million m^3 per year) greater than the right-column plots, indicating the impact of the Amended BDP policy on uncaptured flow within the system. The upper-bound plots display uncaptured flow amounts 1,000,000 AFY (1200 million m^3 per year) greater than the lower-bound plots, indicating the scale of climate uncertainty. By comparison, typical variation within each plot panel is 80,000 AFY (100 million m^3 per year), indicating the influence of the intervention response. The variation within each plot panel is relatively consistent across all six panels, indicating that a given intervention is expected to produce a similar change in uncaptured flow remaining despite very different climate or policy situations. The relative sizes of these influences suggest that coping intervention in the range considered has a more limited effect on uncaptured flow than that of climate or policy influences but that significant uncaptured flow is expected to remain regardless of climate, policy, or intervention.

Capturing Presently Uncaptured Flow. Uncaptured flow in the Tuolumne River watershed is highly relevant to the Regional Water System planning discussion because SFPUC holds the water rights to capture and utilize this flow for water supply.[39] However, a major barrier to more fully utilizing this potential supply is its extremely variable availability, with annual amounts ranging from 0 AF to 5.3 million AF (0 to 6500 million m^3) in a single water year under the Amended BDP simulation. Conceptually, storage capacity is what allows the system to align mismatched timing of supply and demand, but storage capacity is valuable only to the extent that it can be utilized, so the planning analysis must consider how much additional flow could actually be captured by a proposed increase in storage capacity.

Volume-Limited Storage Capacity. Figure 5 shows the relationship between the storage volume added and the additional flow capture that occurs under future climate and policy scenarios. Consistent with the discussion of Figure 4, Figure 5 indicates that additional flow capture (i.e., reduction in uncaptured flow) is largely insensitive to policy and climate. This means that despite uncertainty in these areas, the efficacy of adding storage capacity can be predicted with relative confidence. Under the Existing BDP policy, each acre-foot of additional storage capacity would enable the capture of 0.052−0.054 AFY of additional Tuolumne streamflow (i.e., 1 unit of storage volume would enable 0.052−0.054 units of annual flow capture). Under the Amended BDP policy, a similar capture of 0.049−0.054 AFY/AF is expected (i.e., 1 unit of storage volume would enable 0.049−0.054 units of annual flow capture).

Flow-Limited Storage Capacity. The reservoirs within the Tuolumne River system can accept large inputs during high streamflow conditions but are limited in the total volume they can hold at any given time. Recharge is another possible storage configuration that has a relatively abundant volume but is limited by the rate at which additional water can be added. The former configuration can be thought of as volume-limited storage capacity, while the latter is flow-limited storage capacity such as groundwater recharge. Statewide, the water

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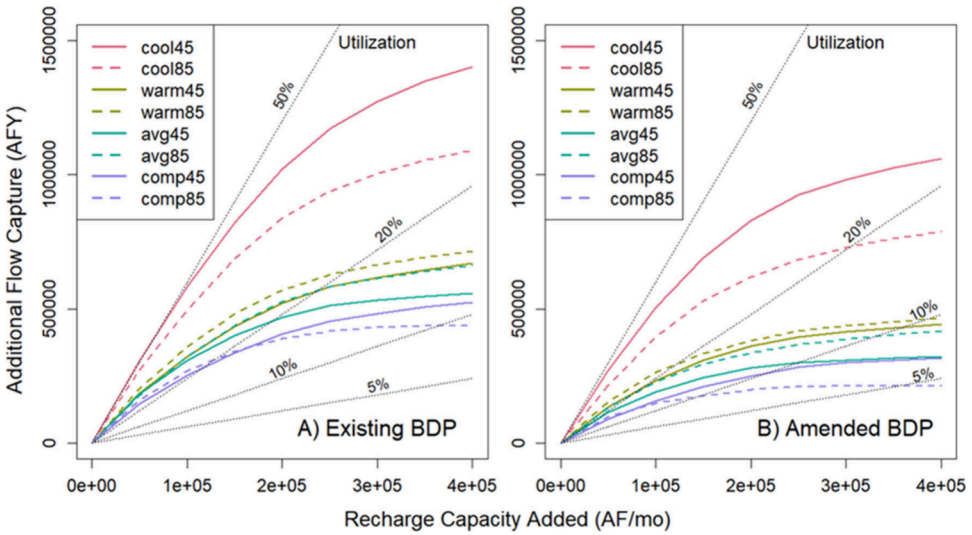


Figure 6. Additional flow capture vs recharge capacity added under (A) Existing BDP and (B) Amended BDP policy scenarios for eight climate scenarios. The marginal utilization (i.e., the additional flow capture expected from the next unit of recharge capacity added) is shown by the variable slope of each series, with reference utilization rates shown by the dashed lines in black. Individual climate scenarios are labeled according to their classification by Pierce et al.[34] (cool, warm, average, and complementary) and their assumed emissions level (Representative Concentration Pathways of 4.5 and 8.5).

storage capacity of underground aquifers is about 20 times larger than that of major surface reservoirs,[40] making recharge a clear opportunity for capturing large volumes, and one that aligns with the state's goal to expand recharge by 500,000 AFY (620 million m^3 per year).[41] In its Alternative Water Supply Plan, SFPUC identifies groundwater recharge in partnership with the Modesto and Turlock Irrigation Districts as a potential project opportunity for continued reliability improvement.[31]

Figure 6 shows the relationship between the recharge capacity added and the additional flow capture that occurs in future simulations. Using the same climate and policy scenarios that have been considered throughout the analysis, Figure 6 describes how much additional Tuolumne River flow could be captured (vertical axis) for a given amount of recharge capacity added (horizontal axis). Just as with reservoir capacity, recharge capacity can be utilized only to the extent that Tuolumne River flow exceeds demand and is available to fill the capacity.

Unlike the constant slopes of the storage volume series in Figure 5, the series in Figure 6 have slopes that flatten out, indicating that the average flow captured per unit of recharge capacity declines as more recharge capacity is added. This makes sense because the first amount of recharge capacity added can be utilized whenever excess flow is available, whereas subsequently added higher capacity can be utilized only when excess flow exceeds previously added recharge capacity. Annotated on Figure 6 are reference lines with slopes corresponding to various utilization rates, defined as the ratio of flow capture relative to recharge capacity. Depending on climate, it is expected that initial amounts of additional recharge capacity will be utilized 24−51% (i.e., 0.24−0.51 AFY flow capture per AFY recharge capacity) under the Existing BDP policy or 15−45% under the Amended BDP policy. Later, as additional recharge capacity approaches 400,000 AF/month (490 million m^3 per month), utilization of new capacity drops to 0−9% under the Existing BDP policy or 0−6% under the Amended BDP policy.

The efficacy of adding recharge capacity varies not only with the amount of capacity added but also with the policy and climate scenario. The unimpaired flow requirement of the Amended BDP reduces the additional flow that can be captured with new recharge capacity. Adding 100,000 AF/month (120 million m^3 per month) recharge capacity, for example, yields 250,000−580,000 AFY (310−720 million m^3 per year) capture under the Existing BDP policy, compared to 150,000−500,000 AFY (190−620 million m^3 per year) under the Amended BDP policy. In both policy cases, the additional capture through recharge could partially or completely offset the average SFPUC ecological flow demand of 240,000−430,000 AFY (300−530 million m^3 per year).

The potential for additional flow capture through recharge (Figure 6) is large compared to the additional capture that could be achieved through volume-limited capacity (Figure 5) such as reservoir storage. SFPUC in its Alternative Water Supply Plan is contemplating adding up to a few hundred thousand acre-feet of storage volume.[31] Under the Existing BDP policy, adding 100,000 AF (120 million m^3) of storage volume is expected to capture 5,200−5,500 AFY (6.4−6.8 million m^3 per year) additional flow, and adding 500,000 AF (620 million m^3) of storage volume is expected to capture 26,000−27,000 AFY (32−33 million m^3 per year). Under the Amended BDP policy, the expected captures are similar: 4,900−6,300 AFY (6.0−7.8 million m^3 per year) and 25,000−27,000 AFY (31−33 million m^3 per year), respectively.

By contrast, additional recharge capacity of 50,000 AF/month (60 million m^3 per month) could capture an additional 150,000−300,000 AFY (190−370 million m^3 per year) under the Existing BDP policy and 90,000−270,000 AFY (110−330 million m^3 per year) under the Amended BDP policy. Using preliminary design assumptions from Holmes,[42] 50,000 AF/month (60 million m^3 per month) of recharge capacity might be achieved by partnering with Central Valley growers to construct 66 recharge basins, each with an area of 50 acres (200,000 m^2) and an infiltration rate of 0.5 feet/day (0.2 m/day). This set of recharge basins would occupy just 3,300 acres

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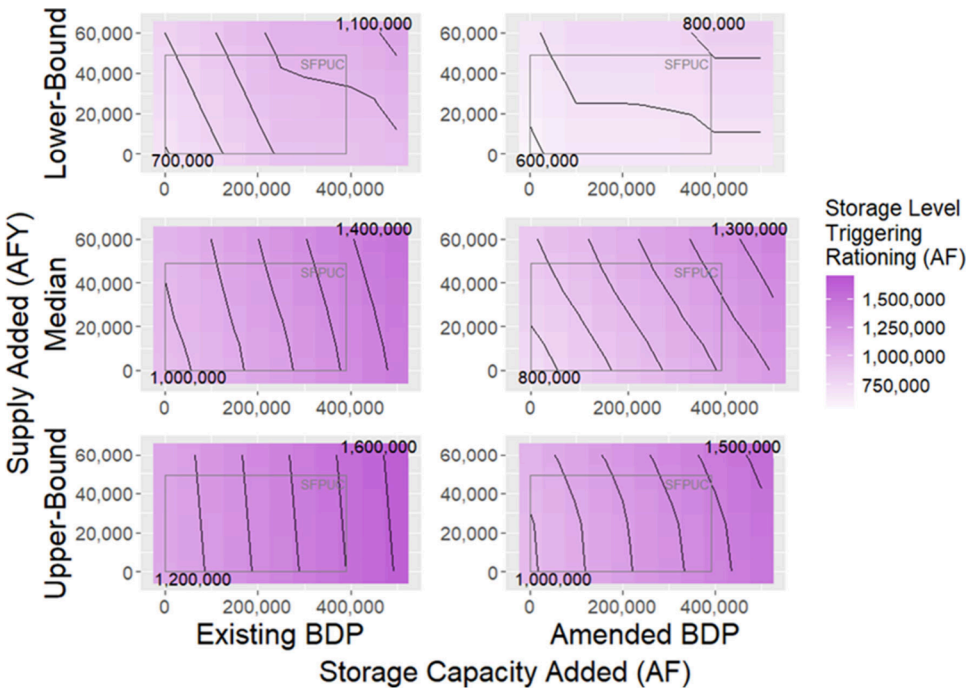


Figure 7. Tenth percentile minimum annual storage, indicating the storage level at which rationing would begin, assuming 90% delivery reliability. The left column corresponds to the Existing BDP policy, and the right column corresponds to the Amended BDP policy. The top, middle, and bottom rows correspond to lower-bound, median, and upper-bound performance across climate scenarios. The axes of each plot show intervention actions: storage capacity added on the horizontal axis and supply added on the vertical axis. Contour lines at 100,000 AF spacing show equal performance across various intervention combinations, and high and low contour values are annotated on each plot. The gray box indicates the intervention range considered in the SFPUC's Alternative Water Supply Plan.[31]

(13 km^2) and could capture flow amounts an order of magnitude greater than what could be achieved by storage volume expansion at the scale being considered in planning.

Management Considerations. *Comparison with SFPUC Reliability Target.* SFPUC sets a delivery reliability target that at least 90% of years require no rationing (Table 2). Based on this target, Figure 7 indicates the Tuolumne storage level at which rationing would begin (i.e., the 10th percentile minimum annual storage). If rationing were to be implemented at an earlier stage (i.e., greater storage level) than the storage levels shown in the figure, this would mean that more than 10% of years would be expected to contain rationing, and thus, the delivery reliability target would not be met. The reference storage levels are shown across dimensions of climate uncertainty (top, middle, and bottom rows), policy alternatives (left and right columns), and coping intervention (vertical and horizontal axes of each individual plot).

Historically, SFPUC has initiated calls for 10% voluntary rationing in November 2021[43] when Tuolumne storage was 860,000 AF (1060 million m^3), at the end of January 2014[44] when storage was 900,000 AF (1110 million m^3), and in 2007[44] when the minimum storage level that year was 890,000 AF (1100 million m^3). Prospectively, based on the results in Figure 7, meeting the reliability target while implementing rationing in this range of storage only works under more favorable climate conditions. Under more severe climate conditions, rationing implemented at this stage would be expected to occur in more than 10% of years, unless coping interventions are implemented in the midrange of what SFPUC is considering (in the case of the Existing BDP policy) or beyond what SFPUC is considering (in the case of the Amended BDP policy).

Role of Conservation. This analysis groups together water conservation and new supplies as one type of intervention, because both strategies target the balance of supply relative to demand. Although they function the same in the water supply balance, these strategies are quite different to enact. Water conservation is a flexible, cost- and energy-efficient solution to bridge the gap between supply and demand in drought.[45] However, on-demand conservation is not without some drawbacks, including restrictions to customers and loss of revenue to utilities using volumetric rate structures.[46] In a drought simulation workshop activity, regulator participants viewed early stage rationing as an appropriately proactive response and essential first step, while utility participants viewed it as potentially damaging customer relations when more severe drought conditions do not follow.[47] Beyond customer perception, behavior-intensive campaigns for water conservation may have adverse effects in other environmental domains like energy use as residents relax practices in other areas while giving particular focus to water.[48]

Ultimately, communities must decide on the right blend of strategies based on their needs, opportunities, and preferences. Some baseline standard of water conservation is expected of everyone, such as the statewide standards for indoor residential water use, which will reach 42 gallons (0.16 m^3) per capita per day by 2030.[49] Beyond this baseline, however, it seems reasonable that some communities may prioritize further conservation to offset the need for new supplies, while other communities may prefer to invest in sustainable supplies or storage to offset the need for rationing. These preferences might depend on factors such as development goals, availability of new supplies, or industry composition and tolerance to water supply variability. Our analysis supports informed

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decision making by showing the water supply outcomes that may accompany various coping interventions that communities might choose.

DISCUSSION

We analyze water supply performance across three key dimensions: climate, policy, and intervention. Though each dimension incorporates uncertainty, it is subject to different levels of control. The coping intervention is the factor most directly controlled by SFPUC, followed by some influence in the ongoing policy negotiations and negligible individual influence over the global climate future. For all three performance metrics considered, climate uncertainty is the factor with the greatest impact on performance. For two metrics (frequency of full storage and uncaptured flow remaining), policy has a greater impact on performance than intervention, and for the remaining metric (minimum storage level experienced), intervention has a greater impact on performance than policy. This means that coping interventions in the range considered can improve low-end performance despite policy impacts and can partially offset other effects of the Amended BDP policy. However, water supply performance is even more sensitive to climate, so climate mitigation makes it worthwhile to pursue coping interventions, even with ongoing policy uncertainty. For reliability-oriented analysis, we recommend planning for severe climate and continuing to assess as additional observations are gathered and future projections are refined. Planning efforts should consider both the level of control and the scale of the impact when determining future priorities.

For entities such as SFPUC with variable water availability year-to-year, the capture and storage of elevated flows present a potentially large opportunity to increase water supplies and improve reliability. This strategy may also facilitate other benefits like flood mitigation, though a planning analysis would have to consider these benefits alongside possible impacts on ecosystems and downstream users. Based on the hydrology of the Tuolumne River and the water rights of SFPUC, a rate-limited storage configuration like recharge has greater potential for capturing additional streamflow than a volume-limited configuration like reservoir expansion. Recharge projects often face fewer regulatory and cost barriers, though they could also involve greater technical and institutional complexity compared with expansion of existing storage infrastructure within the SFPUC service area.

Our study analyzes water supply reliability and performance under realistic yet uncertain climate, policy, and intervention conditions. We study the Bay Area regional water supply in detail and in doing so demonstrate an approach that can be applied to systems elsewhere that are facing water supply stress. A direction for future work would be to conduct stress testing to identify conditions under which the system performance is unacceptable and to compare these conditions to the conditions expected. Such a comparison requires clear standards defining acceptable performance, which points to a continuing need for conversation and knowledge sharing, leading to the development of reliability standards for water supply planning and performance.

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Notes

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